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Energy efficient design of building: A review

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ABSTRACT

Energy saving is a high-priority in developed countries. For this reason, energy-efficient measures are being increasingly implemented in all sectors. The residential sector is responsible for an important part of the energy consumption in the world. Most of this energy is used in heating, cooling, and artificial ventilation systems.With a view to developing energy-efficient structures, this article provides an overview of building design criteria that can reduce the energy demand for the heating and cooling of residential buildings. These criteria are based on the adoption of suitable parameters for building orientation, shape, envelope system, passive heating and cooling mechanisms, shading, and glazing. An analysis was made of previous studies that evaluated the influence of these parameters on the total energy demand and suggested the best design options. This study is useful for professionals who are responsible for decision-making during the design phase of energy-efficient residential buildings.

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1. Introduction

In recent years, significant efforts have been made to improve energy efficiency and reduce energy consumption. The concept of energy efficiency in buildings is related to the energy supply needed to achieve desirable environmental conditions that minimize energy consumption [1].

A suitable heating and cooling design is one of the best methods to reduce energy cost in buildings [2]. To design energy-efficient building, design variables and construction parameters must be optimized [3]. Consequently, it is necessary to identify the design variables that are directly related to heat transfer processes. Ekici and Aksoy [4] summarized the parameters that affect building energy requirements (see Table 1).

The conceptual design phase of a building is the best time to integrate sustainable strategies. When these mechanisms are put into action at the very beginning of the construction phase, this reduces implementation costs as compared to when they are installed in subsequent stages of construction [5].

Evidently, energy-efficient design methods are an added value that benefits the end user. A building design based on energy-saving criteria reduces economic costs throughout the useful life of the building because of its lower energy consumption, and this more than compensates for the greater initial investment. Since there are also fewer CO_2 emissions into the atmosphere throughout the building's life cycle, this benefits society as well.

2. Influence of shape on the energy optimization of buildings

The shape of a building influences the solar energy that it receives as well as its total energy consumption [6]. The radiation hitting a building can increase energy requirements for cooling to up to 25% [7]. Accordingly, building shape not only determines the total area of the façade and roof that receive solar radiation, but also the surface exposed to the outside, and thus to energy losses. When a building is designed, the ratio between its outer surface and the total constructed volume should be as small as possible, tending toward the ideal case of a hemisphere [8]. However, because of design and construction issues, this shape is not attainable in most projects. For this reason, many researchers have begun to study the performance of parallelepiped-shaped buildings and to vary the shape factor in order to find the best model [6,9]. In other cases, they began by defining a hexagonal or octagonal foundation plan [10], a curved or oval foundation plan [11] or one without any specific geometric shape [5] until obtaining the optimal dimensions for the specific geometric context.

Table 1
Parameters that determine building energy requirements [4].

Physical–environmental parameters	Design parameters
Daily outside temperature (°C)	Shape factor
Solar radiation (W/m^2)	Transparent surface
Wind direction and speed (m/s)	Orientation
	Thermal–physical properties of building materials
	Distance between buildings

The variables that are related to building shape and which influence heating and cooling requirements are the following: (i) compactness index; (ii) shape factor; (iii) climate; and (iv) the influence of shape on the life cycle of the building. The characteristics of the building envelope are crucial variables that should be taken into account because they are relevant to the energy requirements for maintaining the building at a comfortable temperature.

2.1. Compactness

The *compactness index* is the ratio between the volume and the outer surface of the building façade. It is related to the building's capacity to store heat and avoid heat loss through its façade. A very compact building is one that has a high volume/surface ratio, where the surface exposed to possible heat losses or gains is as small as possible. The relative compactness of a building is defined as the ratio between its compactness index and the compactness index of a reference building as shown in Eq. (1).

$$RC = \frac{(V/A_{\text{ext}})\text{building}}{(V/A_{\text{ext}})\text{ref}} \tag{1}$$

Fig. 1 shows two buildings with the same volume but with different compactness indices.

The compactness index is a ratio that provides an idea of how a building can be cooled and heated [12], and which influences energy consumption [13]. The overheating of a building because of a high compactness index can be compensated by the installation of passive cooling systems.

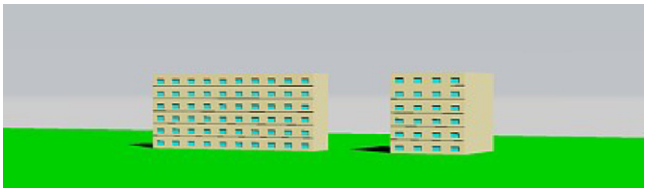

Fig. 1. Buildings with different compactness indices: (i) building with a compactness index of 3.45 (left); (ii) building with a compactness index of 5 (right).

2.2. Shape factor

The shape factor is the ratio of building length to building depth. Along with orientation, this factor defines the percentage of the façade exposed at each cardinal point. Both factors are generally studied together [4,9,14,15]. By combining the optimization of shape and orientation, it is possible to obtain benefits that can lead to heat energy savings of 36% [9].

Florides et al. [12] quantified the effect of the shape factor on energy requirements for the heating and cooling of a building. Their conclusion was that the best position for a rectangular house is for the longest wall of the building façade to face the south. A model with a 1/2 shape factor (less wall surface with a southern orientation) requires almost 8.2% more energy for heating. This percentage increases considerably (26.7%) when there is more roof insulation since the heating gain is prevented by the roof cladding.

Mingfang [6] studied the influence of building length, depth, and width parameters on the solar radiation received by a parallelepiped-shaped building. In his study, the volume was kept constant and Eq. (2) was applied.

$$\frac{Q}{Q_0} = \frac{(q_s+q_N)^3\sqrt{\lambda\beta}+(q_E+q_W)\times\sqrt[3]{\lambda^{-2}\beta}+q_H\times\sqrt[3]{\lambda\beta^{-2}}}{q_s+q_N+q_E+q_W+q_H} \quad (2)$$

where Q/Q_0 is the relative solar radiation received by the external surface of the buildings; q_S, q_N, q_Z, q_W, q_H are the solar radiation on the south-wall, north-wall, east-wall, west-wall and roof per unit area in daytime; λ is the length/depth ratio of the building; β is the height/depth ratio of the building.

This equation gives the optimal building proportions that minimize the direct solar radiation received. By this method, the total solar radiation on the building will decrease as much as 4% in comparison with radiation on a cubic building

2.3. Climate and shape optimization

In very cold climates, more heat escapes through the building envelope than the amount of heat that can be gained by increasing the surface receiving solar radiation. Therefore, the increase in the shape factor (more external building surface for the same volume, lower compactness index) is proportional to the increase in the energy required for heating [16]. In warm climates, this proportion is not direct, and a fixed type of building performance cannot be determined.

2.4. Cost of the life cycle and shape of the building

Marks [10] calculated construction and heating costs, depending on building shape. He considered a curve-shaped building and a polygonal-shaped building. For both possibilities, the optimal building shape is conditioned by the years of a building's service life considered in the calculations. For example, in the case of a polygonal shape for short heating periods, building shape approximated an octagon. It is necessary to establish a standard criterion for the years of the building's service life that must be considered when the economic cost of the energy demand is evaluated.

The *life cycle of a building* is the period from its conception until the end of its service life or demolition. The life cycle includes the phases of design, construction, occupation, use, and maintenance, and dismantling. This process quantifies and evaluates the flow of material and energy in the system [17]. It is possible to ascertain the distribution of the environmental impact throughout the processes and stages that make up the building's life. Fig. 2 describes the phases in the life cycle of a building [18].

Between 80% and 85% of the total energy consumption during a building's life cycle occurs in the use or occupation phase [19]. This includes the energy costs of heating, cooling and ventilating the building, lighting, equipment operation, water supply, water heating, and wastewater treatment [17].

Wang et al. [5] studied the impact of building shape on energy demand. They calculated the life-cycle cost (LCC) and life-cycle environmental impact (LCEI) with Eqs. (3) and (4).

$$\mathrm{LCC}(X) = \mathrm{IC}(X) + \mathrm{OC}(X) \quad (3)$$

$$\mathrm{LCEI}(X) = \mathrm{EE}(X) + \mathrm{OE}(X) \quad (4)$$

where IC is the initial construction cost; OC is the current worth of life-cycle operating costs that comprise energy consumption cost and peak demand cost; EE is the environmental impact in megajoules (MJ) caused by the building construction; OE is the environmental impact (MJ) caused by the building operation for heating, cooling, and lighting.

The solution with the lowest life-cycle cost has a shape that is roughly a regular polygon (this coincides with the fact that the most efficient shape is a cube). In contrast, when the environmental impact of the building and thus, its energy demand (i.e. impact of its construction, heating and cooling, and lighting) are minimized, the model with the lowest environmental-impact cost is the one that has the longest section of the façade facing south.

Adamski [11] solved the controversy between the most cost-efficient building shape and the most energy-efficient building shape. For this purpose, he formulated seasonal heating and construction costs based on building shape variables, such as height, volume, length of the curves defining each façade, and orientation angle. The optimal solution obtained was composed of semi-circular boundaries for the northern section of the building and a curve for the southern part. He found that an oval base had a better thermal performance than a circular or a square base. The more or less oval shape of the base was directly related to the years of the building's service life being considered. As the number of years increased, the values of the eccentricity axis of the oval became smaller and the result, less circular.

3. Orientation

Among the parameters that intervene in the passive solar design of buildings, orientation is the most important and the one that has been most frequently studied [20]. The level of direct solar radiation

Fig. 2. Building life cycle.

received on the building façade depends on the azimuth in the wall, and thus, on the orientation angle of the building [6]. The orientation of the façade also influences other parameters of passive design, such as shading [21] or the performance of the solar envelope [20]. Benefits derived from optimal building orientation are the following:

- It is a low-cost measure that is applicable in the initial stages of project design.
- It reduces the energy demand.
- It reduces the use of more sophisticated passive systems.
- It increases the performance of other complex passive techniques.
- It increases the quantity of daylight, reduces the energy demand for artificial light, and contributes less to the internal heating load of the building.
- It improves the performance of solar collectors.

It is generally agreed that a southern orientation is optimal for gaining heat in the winter and for controlling solar radiation in the summer. As a general rule, the longest wall sections should be oriented toward the south [6]. However, orientation can also be studied with a view to optimizing other parameters such as the total solar radiation received, building shape, ground plan surface, and the annual energy demand.

3.1. Orientation and solar radiation received

Gupta and Ralegaonkar [15] optimized the orientation of a building for various shape factors with the objective of minimizing the solar radiation received in summer and maximizing it in the winter. The total energy gained by this radiation was calculated by applying Eq. (5).

$$E = A \times \int_{\omega_1}^{\omega_2} (0.834 \times H) \times \left(\frac{\cos\ i}{\cos\ \theta_z}\right) d\omega \tag{5}$$

where A is the surface area; H is the monthly mean daily global radiation on a horizontal surface; i is the incidence angle; $d\omega$ is the hour angle at sunrise or sunset; θ_Z is the zenith angle or polar angle.

The authors optimized the value of the solar radiation received during the months of the most extreme climate conditions (June and December). This was done by using different shape values and varying the orientation angle from 0° to 180°. This method can be used to find the optimal orientation angle for the reception of minimum solar radiation in summer and maximum solar radiation in winter. The authors concluded that the optimal orientation was generally when the longest wall sections were oriented toward the north and south.

Chwiduk et al. [22] studied the amount of solar radiation received by elements with different slopes and azimuth angles. For this purpose, they used two radiation models: (i) a diffuse isotropic sky model [23]; (ii) an anisotropic sky model [24]. They calculated the most suitable parameters for the same surface (wall or roof) to receive the maximum possible solar radiation in the winter and the minimum possible radiation in the summer. The influence of the tilt and orientation of the surface on the radiation level was most perceptible in the summer. They concluded that in order to maximize the solar energy gain during the whole year, the azimuth angle of the surface should be approximately 15° even though angles between −15° and 45° also provided good results. This procedure is especially useful for the installation of solar panels. It can be used to calculate the energy that they receive, and consequently, their effectiveness.

3.2. Orientation and shape

Aksoy and Inalli [9] studied the relation between building orientation and heat demand. For this purpose, they used three models with different shape factors (1/1, 1/2 and 2/1), with and without heating insulation on the façade. They rotated the buildings 80°, and obtained data at 10° intervals. Fig. 3 shows the heating energy saving rates, depending on the shape factor of the building and the azimuth angle of the north-south axis compared to a building without any insulation.

By combining shape factor, orientation, and heating insulation, a heating energy saving rate of up to 36% was achieved. It was determined that the best orientation for rectangular buildings was when the longest walls were oriented toward the south. In square buildings, the highest heating demand values were obtained when the building was rotated at an intermediate angle of 45°. They become lower as the values 0 and 90 or multiples of these values were approximated (in other words, when one of the façades of the building began to face south). In buildings without insulation and with different building shapes a heating energy saving rate of 1–8% was obtained, depending on the orientation of the building.

Florides et al. [12] studied the relation between building orientation and shape. For a square building, they found that the heating demand reached its minimum value when the building façade was directly oriented toward the four cardinal points. In a rectangular building, the heating demand was lower when a smaller portion of its surface faced east. According to the authors, the eastern orientation of the building surface was what most contributed to an increase in the heating energy demand.

3.3. Orientation and ground plan

Morrissey et al. [20] determined that buildings with a small ground plan were less sensitive to changes in orientation. In other words, they showed better thermal performance even when their orientation was modified in comparison to buildings of larger dimensions (>200 m^2). The ground plan surface was found to be the most crucial factor in terms of adaptability to orientation change. They analyzed data pertaining to the heating and cooling energy demand obtained from a modeling experiment that focused on 81 different residential building designs. They obtained the statistical correlation between these energy demand values and the four variables with the greatest repercussion on the thermal performance of the building (i.e. ground plan surface, wall/floor ratio, total external surface, and total window surface). The results showed that it was more difficult for larger residential buildings to perform at acceptable levels of energy efficiency. The most energy-efficient houses were less sensitive to orientation changes.

3.4. Building orientation and energy demand

The study of the optimal orientation of a building evidently increases energy saving [14]. Table 2 shows the energy saving in heating and cooling that resulted when a model of a large building was rotated 30°, 45° and 60° in regards to the southern axis. The greatest energy saving was obtained when the longest walls were rotated 30% to the south.

According to Littlefair [25], most of the books, user guides, and manuals on passive solar techniques recommend that buildings should face southwards, although there is a growing consensus that the best option is to orient buildings 20–30° to the south.

Shaviv [26] studied the orientation of the glazing surface of a building, and obtained the results shown in Table 3. She concluded that in order to obtain maximum energy saving, the main glazing surface should face south, especially in countries with a hot

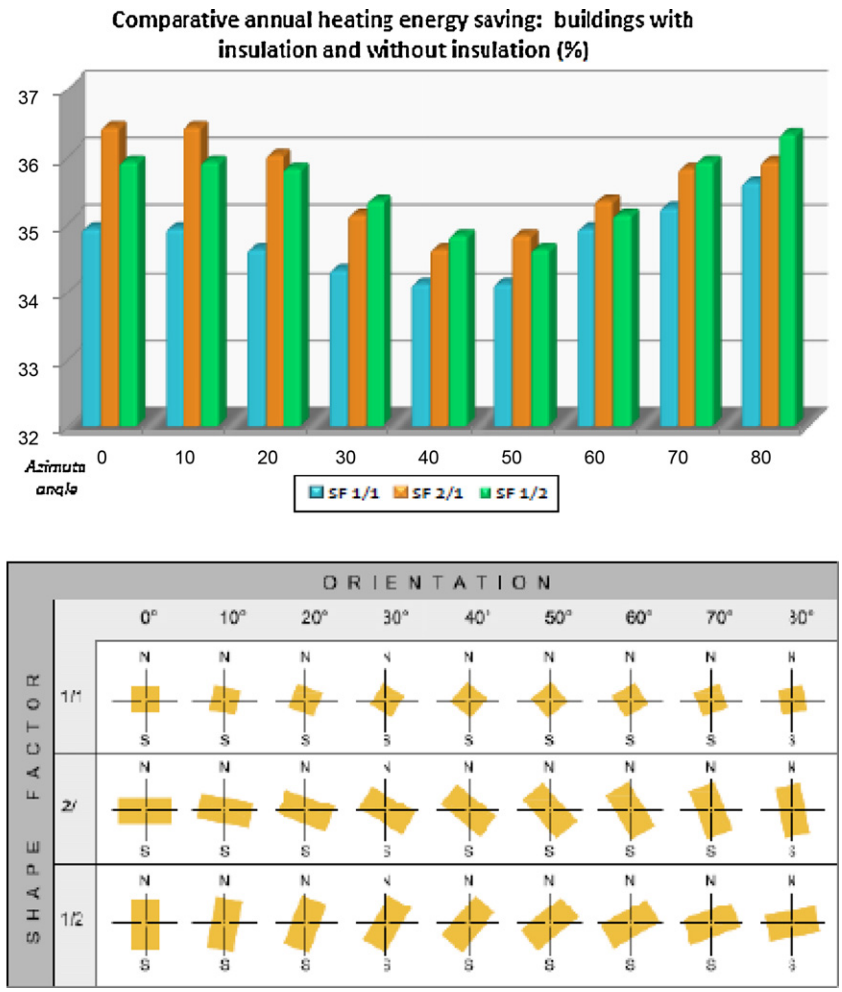

Fig. 3. Heating energy saving, depending on shape factor and orientation [9].

and humid climate. If this is not possible, the building should face southeast.

4. Influence of the building envelope in the energy demand

The building envelope (foundation, roof, walls, doors, and windows) and the operation period of the heating system are the factors that have the greatest impact on the total energy consumption of the building [27]. The envelope determines interior climate conditions, and thus, the additional energy demand for heating and cooling. Actions on the elements that make up the building envelope can have a positive impact on certain energy requirements and have a negative affect on others. Consequently, it is necessary to evaluate the performance of the building as a whole [28].

Table 2
Energy saving obtained, based on the orientation of a rectangular building [14].

Energy saving ($/year)			
Installation	Change in orientation (in reference to the south)		
	30°	45°	60°
Heating	29	26	36
Cooling	58	15	0
Heating, ventilation, and air conditioning (HVAC)	53	38	23
Total	140	79	59

4.1. Heat transfer formulas: optimization of the limit U value

Design parameters that affect indoor thermal comfort and energy conservation are orientation and shape, as well as the optical and thermophysical properties of the façade or building envelope. The heat transfer coefficient (U) determines heat loss per unit area of the components of the building envelope. It is frequent for authorities to establish a maximum value of U in order to control heat loss in buildings and guarantee the comfort of the occupants.

Table 3
Energy consumption of an office unit at three different orientations [26].

	Energy consumption at three orientations (kWh/year)					
	South	%	East	%	West	%
Heating	186	0	231	24	219	18
Cooling	281	0	286	2	369	31
Total	467	0	517	11	588	26
Tmax (°C)	26.4		26.6		27.0	

For Oral and Yilmaz [29], the transfer coefficient of the building façade should be calculated on the basis of the compactness index (total façade area/volume). The maximum heat loss in a reference building can be calculated with Eq. (6).

$$q = U_0(t_i - \overline{t_{eo}})(1 - X) + U_g(t_i - \overline{t_{eg}})X \tag{6}$$

where q is daily heat loss; U_0 and U_g are heat transfer coefficients of the opaque components and the transparent components, respectively; t_i is the inside temperature; t_{eo} and t_{eg} are the mean sol–air temperatures of the opaque and transparent components; X is the transparency ratio.

Using graphical methods, these authors determine the maximum possible U for values with other compactness indexes.

The method, which was developed by Manioğlu and Yilmaz [27], obtained the combination of building envelope and heating system operation that provided thermal comfort conditions at minimum cost during the life cycle of the building. This procedure determined the optimal materials of the envelope, which as a whole, satisfied the maximum heat coefficient transfer of the building. For this purpose, they took into account the best combination of materials that provided this U value, the total heat loss, and the economic costs of the heat system operation as well as of the life cycle of the components. For each envelope that satisfied this condition, they studied various operation periods until finding the most economic and energy-efficient solution. It should be underlined that the optimal solution might not coincide with the option producing the lowest heat loss through the building façade.

The effectiveness of actions to improve the thermal performance of the envelope depends on building type and use. It has been shown that in residential buildings with a reduced window/wall ratio, the use of an optimal level of insulation in the building façade considerably reduced the energy demand, especially for heating [30]. In contrast, this procedure is not effective in buildings whose façade is predominantly made of glass, as is the case of many commercial office buildings [28]. The improvement in the U value of these buildings does not involve a reduction in outside heating gain, whereas an action affecting the type of glazing can improve thermal performance.

4.2. Building insulation and economic analysis

Jinghua et al. [31] used an eQUEST simulation to study the effect of the thickness and the position of building façade insulation on the total energy demand, among other things. By using a combined optimization strategy for insulation, window/wall ratio, glazing and shading system, they achieved a reduction of up to 25.92% in the total heating and cooling demand. However, after a certain insulation thickness threshold was surpassed, the energy reduction continued, but at a significantly lower rate.

The position of the insulation layer (external surface, internal surface, within the wall itself) has little repercussion on the annual electricity consumption although a minimum consumption is obtained when the insulation is located on the inside wall surface. In contrast, if the cooling energy consumption is considered separately, the insulation placed within the wall was found to consume more electricity than the other options. The minimum electricity consumption value for cooling was obtained with an insulation layer of 25 mm, where the minimum value for heating was obtained with an insulation layer of 100 mm.

These differences mean that an economic analysis is needed to calculate the insulation layer thickness that is most cost-effective and energy-efficient. However the results of such an analysis may indicate that the most economical insulation layer thickness does not correspond to the optimal insulation obtained for each element individually, or to the insulation providing the lowest heat transfer value U in the building [30]. In this regard, there are two methods that have been used to perform an economic evaluation of building façade insulation.

Çomakli and Yüksel [32] used the concept of present worth factor (PWF) to find the optimal thickness of building façade insulation. They formulated Eq. (7), which determines the most cost-effective insulation for various economic parameters, insulation materials, and climate conditions.

$$x_0 = 293.34\sqrt{\frac{\mathrm{PWF\,DD}\,C_f k}{C_i H_u \mu}} - kR_r \tag{7}$$

where DD represents degree days (°C day); C_f and C_i are the cost of fuel and insulation, respectively; H_u is fuel heating power; R_r is the thermal resistance of the façade; μ is the heating system efficiency; k is a numerical constant.

The PWF is formulated by Eq. (8).

$$\mathrm{PWF} = \frac{1 - (1 + r)^{-N}}{r} \tag{8}$$

where N is the number of years in the building's life cycle, and r is the interest rate adjusted for inflation, according to Eq. (9).

$$r = \frac{I - g}{1 + g} \quad (I > g) \tag{9}$$

where I is the interest and g is the inflation.

Optimal insulation thickness was found to be inversely proportional to the cost of the insulation material and its thermal conductivity. An overly thick insulation layer resulted in an unnecessarily high initial cost that was not compensated by the fuel reduction. Furthermore, a very thin insulation layer was more economical at the beginning, but ultimately generated higher fuel costs. These authors found that the optimal insulation thickness maintained a linear relation with the PWF.

In the study by Lollini et al. [30], the optimization of the insulation levels of the opaque components of the building envelope was performed by carrying out a three-level analysis: energy, economy, and environment. The calculations were performed with EC501 simulation software, created to evaluate the energy and cost performance of various thermal insulation combinations for two reference buildings. They also used the PWF of the insulation material, which represents the cost difference between the initial investment in additional insulation in reference to the estimated annual cost savings during the building's life cycle. They applied formulas created by Augelli [33], and calculated the PWF by applying Eq. (10) with parameters related to the heat transfer value of the insulation and its mean thickness.

$$\mathrm{NPV} = R - \mathrm{In}\nu = ((U_0 - U) \cdot 24 \cdot \mathrm{DD}^* \cdot \mathrm{EPC}) - (m \cdot s + q) \tag{10}$$

where DD* is a parameter that depends on the level of insulation and inside gains; U_0 and U are the reference heat transfer and the insulation heat transfer, respectively; R is the annual energy saving; Inv is the initial investment; s is the thickness of the insulation layer; m and q are the fixed costs and the variable costs of the building material.

Based on this equation, the heat transfer value U of the material can be optimized. Eq. (11) expresses the energy present cost (EPC).

$$\mathrm{EPC} = \frac{P_0 \cdot r \cdot [(r/\nu^N - 1)]}{\mu \cdot \mathrm{NVC} \cdot (r - \nu)} \tag{11}$$

where P_0 is the annual cost of city gas; μ is the overall efficiency of the heating system; NVC is the net calorific value of the gas; N represents the life cycle (i.e. 30 years); r and ν are financial indicators of inflation and interests, respectively.

These results seem to agree with the previous ones [31]. Effectively, once a critical threshold has been reached, a massive increase in the thickness of the insulation layer does not lead to a significant improvement in the heating performance of buildings. Even though

the heating demand diminishes as the insulation level increases, the dependency relation between these two elements is somewhat less well defined. Consequently, the effectiveness of increasing the insulation (or reducing the heat transfer of the building envelope) as a method for reducing heating demand is effective only up to a certain point, after which a massive increase in insulation continues to produce a reduction in the heating demand, but at a lower rate.

Even so, these authors affirm that this may occur because the addition of insulation takes place in different parts of the building (walls, roofs, floors) that have different weights in the overall external surface, resulting in a discontinuity of the heating load profiles.

The specification of the most cost-effective overall insulation level is not as precise as in the case of separate building components [30]. As the level of building insulation increases, the PWF also increases until it reaches an optimal level after which for an overly insulated building, there is only a slight increase in the PWF. The optimal insulation level chosen by the authors was the level that produced the highest PWF, which is compatible with the lowest Pay Back Rate (PBR).

4.3. Environmental study of the building envelope

Other studies have opted for performing an environmental analysis instead of a cost analysis. Pulselli et al. [34] carried out a thermal and energy analysis as well as an emergetic evaluation to evaluate the environmental cost and benefits of building façades. Emergy was evaluated by means of the procedure created by Odum [35], in which *emergy* is defined as the amount of solar energy used, directly or indirectly, to obtain a product or final service. Three models were compared:

- A conventional air cavity wall with insulation.
- A cavity wall with an external cork covering added.
- A ventilated wall with external brick panels fixed on an extruded frame.

The study was performed for cold, warm, and hot climate conditions. The authors concluded that the building wall with the additional insulation layer as well as the ventilated wall had a better thermal, energy, and emergy performance. In terms of natural resources, the emergetic analysis assigned a more important role to regions with a hot and warm climate. This was due to the fact that the reduction in cooling demand provided greater environmental benefits than the reduction in heating demand. Generally speaking, air conditioning systems operate with electricity (which has a greater environmental impact), whereas heating systems use other fuels.

Chel and Tiwari [36,37] studied the environmental impact of a mud house by estimating the thermal performance, embodied energy, energy payback time, CO_2 emission mitigation potential and corresponding carbon credits. The adobe house temperatures are temperate throughout the year and it leads to energy saving potential. It was determined an annual heating and cooling energy saving potential as 1481 kW h/year and 1813 kW h/year. The authors estimated that on an average adobe or mud-house can mitigate 5.2 metric tons/year CO_2 emissions in to the atmosphere. The authors concluded that it must be chosen not only the material with the lower embodied energy but also with the lower environmental impact.

5. Shading on buildings

Shading on building façade elements controls the amount of solar radiation received by the building. This strategy provides positive results when actions are performed on the building façade cavities since these are the elements that transmit the highest level of radiation to the inside of the building.

5.1. Shading coefficient

A suitable shading coefficient saves energy throughout the year [38]. The American Society for Heating, Refrigerating and Air-conditioning Engineering (ASHRAE) includes the shading coefficient (SC) among the factors that should be taken into account in the calculation of the heating and cooling demand of a building. This coefficient is defined as the ratio of solar heat gain through a given fenestration system under a specific set of conditions to the solar heat gain through single glazing of standard 3 mm clear glass, as shown in Eq. (12).

$$\mathrm{SC} = \frac{\text{solar heat gain factor of fenestration}}{\text{solar heat gain factor of reference glass}} \tag{12}$$

One of the problems of establishing a fixed shading coefficient is that the angle of incidence of solar rays does not remain constant [39]. Various research studies have been carried out to develop a reliable method or system of calculating this shading coefficient [39,40].

The procedure to calculate optimal shading proposed by Yang et al. [38] transforms the energy saving from shading in summer and solar penetration in winter into energy savings in the equipment. They used Eq. (13) to calculate the total annual energy savings, depending on the value of the shading coefficient:

$$\mathrm{SEC} = \frac{Q_S \times (1 - \mathrm{SC} + Q_W \times \mathrm{SC})}{Q_S + Q_W} \tag{13}$$

where SEC is the solar radiation synthetic energy savings coefficient; SC is the shading coefficient; Q_s is the summer energy savings gain from shading; Q_w is the winter energy savings gain from solar penetration.

In hot climates, there are greater energy benefits with a high shading coefficient since heating gains are reduced. However, the shading coefficient should not be excessively high [38]. If these energy gains are transformed into economic costs, in terms of the price of fuel used for the heating and cooling systems, the economic balance is not as close to a high shading coefficient as the energy balance.

5.2. Effectiveness of shading devices

In the same way as with other energy-saving devices in the building, the use of shading devices can be beneficial at certain times of the year though they are counter-productive at other times [38]. Control of shading is necessary in order to assure thermal and visual comfort inside the building. Passive shading systems favor a reduction of the heat gained by the building, which means that cooling systems are not operated as frequently. Nonetheless, they have the drawback of reducing daylight availability [41]. Protecting buildings from excessive shading increases the hours of daylight and reduces the use of artificial light. This generates energy savings as well as cost savings, and also provides occupants with greater comfort since daylight is more comfortable than artificial light. The reduced use of artificial light also brings with it a reduction in the heat generated in the building [25].

Shading can be provided by neighboring elements or come from systems incorporated in the building itself. As the use of solar energy (e.g. solar panels) becomes more widespread, there will be a

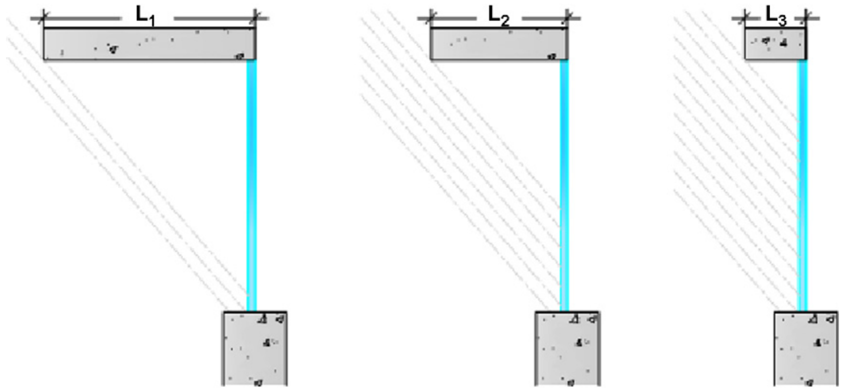

Fig. 4. Effect of overhang on incident radiation through a window.

greater need to standardize methods for the evaluation of shading on buildings as a consequence of their proximity to other constructions. The energy benefits of shading are obviously conditioned by the climate of the building site.

5.3. *Energy benefits of the shading in hot climates*

The control of shading elements, lighting as well as heating and cooling components could significantly reduce peak cooling load and energy consumption for lighting and cooling, while maintaining suitable heating and lighting conditions [41].

5.3.1. *Roller shades and overhang*

One problem with shading devices, such as roller shades and overhang, is that they are often designed to remain in one position. This evidently favors energy saving in certain situations, while hampering it in others. According to Bouchlaghem [40], shading devices should be designed so that their position can be adapted to the season of the year. The building would thus be shaded in the summer, but not in the winter. This study performed a TRANSYS simulation which showed that by increasing the solar protection provided by overhang, the annual cooling demand decreased as the heating demand increased [12]. This was due to the fact that these devices blocked part of the solar radiation that is so beneficial in winter. Both positive and negative effects were accentuated when the windows were more oriented toward the south since they received more annual solar radiation. As a result, it could be advantageous to use long projecting horizontal overhangs that can be folded back or removed in winter.

The use of mobile shading systems is more beneficial in regards to natural illumination and to lower energy consumption. Tzempelikos and Athienitis [41] compared the effectiveness of fixed passive shading systems with a simple automatic shading system (automatic roller shades). They had them operate alternatively and calculated the light transmitted into the room by applying Eq. (14).

$$D = \frac{E_b * \tau_b + E_d * \tau_d}{1 - \rho\tau_{rs} * \rho_w} \tag{14}$$

where D is the transmitted radiation into the room; τ_b is the beam window transmittance; τ_{rs} is the roller shade transmittance; ρ_{rs} is the roller shade reflectance.

They thus managed to increase the annual daylight availability by 20%. This led to energy savings in artificial light as well as to greater productivity.

Overhangs avoid the entry of direct radiation through the window at certain times of the day. This has the advantage of regulating the entry of excessive heat and daylight as shown in Fig. 4.

Florides et al. [12] quantified the effect of overhang length on energy demand. They found that a longer horizontal overhang reduced the cooling demand and increased the heating demand.

Robert and Jones [42] measured the ratio between overhang dimension and winter solar radiation. This study describes a method to calculate the optimal overhang dimensions for a specific emplacement. When these dimensions were surpassed, the winter heat loss was not compensated by the reduction of solar radiation in the summer.

5.3.2. *Self-shading*

An appropriate building design can cause the building to shade itself without the need of additional elements. This can be beneficial especially in the case of isolated buildings that are subject to excessive quantities of direct solar radiation. This idea led to the concept of *self-shading*. The most widely used building shape for this purpose is the inverted pyramid [21]. Certain architects opt for making all walls slant inwards, such as in the Tempe City Hall. One problem with such a design is that since all windows slant inwards as well, less of the window surface receives solar radiation, and consequently, window size must be increased. This inconvenience

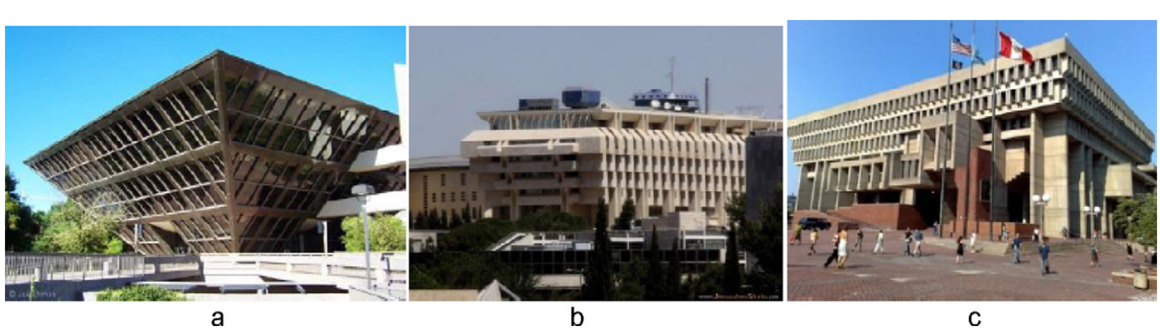

Fig. 5. Self-shading buildings [21].

can be avoided by using a stepped inverted pyramid design (e.g. the Bank of Israel). In such a building, the window surface is not affected. Fig. 5 shows examples of buildings with this design.

Depending on the degree of inclination of the building façade, the shading period is of longer or shorter duration. When the angle is greater, the building will be shaded for a longer time. Because of this, the use of self-shading façades is only useful when a limited number of hours of shading are needed since in the opposite case, the walls would be excessively inclined.

5.4. Energy benefits of shading in cold climates

The amount of sunlight that enters a building through the windows depends on the latitude, climate, daylight availability at the emplacement, incident angle of solar radiation, obstruction created by other buildings, and the energy reflected by neighboring elements [43]. The procedures used to study sunlight availability at a specific site or location can be classified as follows:

- Graphical methods [44].
- Analysis of the obstruction angle [25].
- Solar envelope [45].
- Computer simulation methods [46].

5.4.1. Shading cast by neighboring buildings

Site layout has the greatest impact on passive solar heating. According to Littlefair [44], the loss of solar light and the heat gain from neighboring constructions are characteristic parameters of any large city. High buildings and other nearby constructions affect the distribution of natural light inside a building and block the entry of sunlight, particularly in the winter. Fig. 6 is an example of an obstruction angle. There is a need for more research on how obstructions can affect the reception of diffuse radiation. As the urban area becomes denser, current methods for the calculation of solar radiation obstructed by the proximity of other buildings become less precise.

The obstruction angle can be calculated by graphical methods, using diagrams of the sun's path. Fig. 7 depicts a solar diagram for a latitude of 55°, and shows the impact of obstruction angles of 10° and 40°. As can be observed, an obstruction angle of 10° allows the building façade to receive most of the solar radiation, whereas an angle of 40° blocks all sunlight from September to March.

Table 4
Light obstruction angles due to nearby elements, depending on emplacement latitude [25].

Latitude	Climate	Obstruction angle (°C)
35	Mediterranean	40
40	Warm Mediterranean	35
45	Temperate	30
50	Temperate	25
55	Moderately cold	22
60	Sub-arctic	20

It is thus possible to specify the limit values for angles of neighboring elements. When these angles are surpassed, the occupants of the building perceive a reduction in daylight with the subsequent increase in the demand for artificial light. Table 4 shows the maximum value of the obstruction angle for which a building can keep receiving sufficient sunlight, depending on the latitude of its emplacement.

Access to passive solar radiation in buildings is an inalienable right and should be protected by national law or local urban planning [44].

The need to receive solar radiation in winter should not only be taken into account during the project design phase of the building, but also during the design phase of entire neighborhoods including sidewalks and open spaces. This means that each district should be projected as an optimized system which should receive the appropriate amount of sunlight to make it energy efficient and to guarantee the comfort of its occupants. The design guidelines

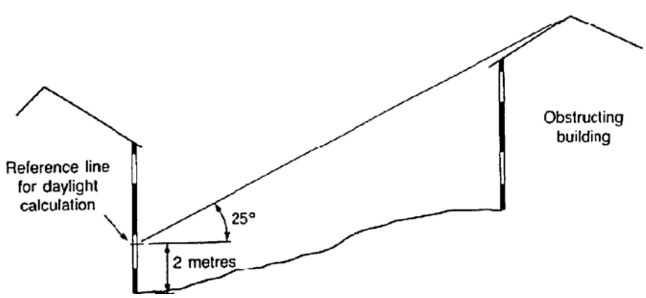

Fig. 6. Section of a building showing an obstruction angle of 25° [25].

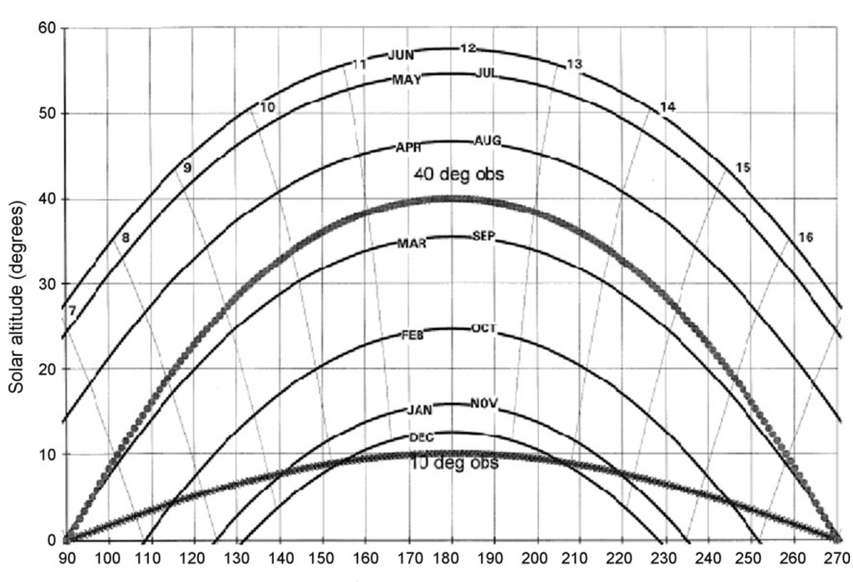

Fig. 7. Solar diagram for a latitude of 55° with obstruction angles of 10° and 40° [44].

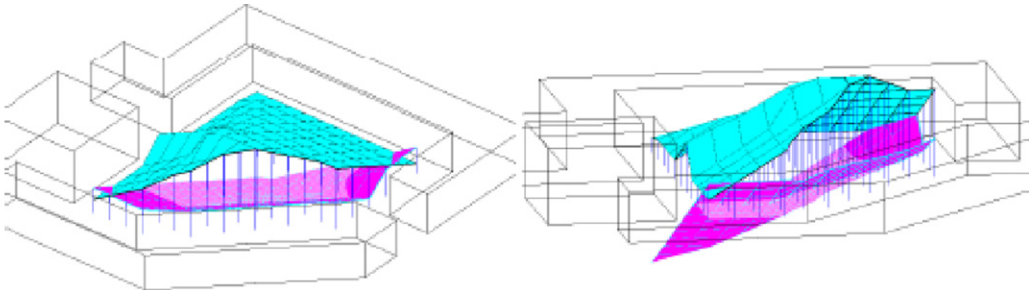

Fig. 8. Solar volume as the conjunction of the solar rights envelope (upper plane) and solar collection envelope (lower plane) [45].

proposed by Capeluto and Shaviv [45] are based on obtaining the solar volume of buildings, depending on their location and orientation, as shown in Fig. 8.

These authors use such graphical representations to determine building height, street width, and overall building shape orientation in order to obtain the highest possible urban density levels combined optimal solar exposure.

6. Passive systems

Passive techniques of temperature control and inside humidity were first employed in ancient times. With the widespread use of electrical energy, these methods gradually became obsolete [47]. However, in developed countries, especially those with very hot climates, there is currently a growing interest in these low-cost systems for the passive cooling of buildings [48]. These mechanisms are based on the natural convective movement caused by the different densities of cold and hot air [49]. However, the term *passive* does not exclude the use of a fan or pump to enhance system performance. Even though passive systems highlight the use of natural heating or cooling sources, some type of power is necessary to initially start operation. Since the passive heat transfer system is low cost and simple, the ratio of power consumption to the total consumption of the installation is relatively low [48]. The type of passive system chosen will influence different aspects of the design.

6.1. Passive cooling

Passive cooling is defined as the limitation of heat inside buildings by means of natural processes to expel heat into the atmosphere (i.e. convection, evaporation, and radiation), or into the ground beneath buildings (i.e. conduction and convection) [47]. This section follows the classification of passive cooling systems elaborated by Givoni [50] and summarized in Fig. 9.

The efficiency of passive cooling systems is closely related to the nocturnal and diurnal outside temperature gradient with maximum temperature peaks, depending on the location. Certain passive cooling procedures are immediately effective (e.g. natural ventilation and direct evaporative cooling). Other systems store cold energy in the structural mass of the building. The main factor that constrains the efficiency and applicability of such systems is the limited capacity of the structural mass of the building to store thermal energy [48]. The following sections are a summary of the most important types of passive cooling methods listed in Fig. 9.

6.1.1. Natural ventilation

Natural ventilation is also known as *comfort ventilation*, and is based on the positive psychological effect of a suitable air flow throughout the building. In hot humid climates, this effect considerably improves the feeling of well-being of the occupants, even when the temperature and humidity conditions of the air from the outside is the same as those of the inside air. Therefore, daily ventilation is necessary to minimize the psychological effect of high humidity and improve the convective loss of body heat [48]. The term *advanced naturally ventilated building* was coined to designate buildings that use the stack effect (natural movement of air due to differences in temperature and density) to drive an air flow [51]. Fig. 10 shows an example.

6.1.2. Nocturnal convective cooling

Nocturnal convective cooling cools the structural mass of the building by means of nocturnal ventilation. Closing the building during the day keeps indoor temperatures from rising. This procedure is especially applicable in arid or desert regions with high daytime temperatures, and where the minimum night temperature in summer is lower than 20 °C. It is also effective in non-residential buildings with a high cooling demand and with no night occupation, such as academic buildings or offices. Nocturnal ventilation helps to reduce demand peaks and operation periods of electrical cooling equipment. Research has shown that the mean temperature of a building can be reduced by up to 3 °C with this type of ventilation [50].

6.1.3. Radiant cooling

Radiant cooling requires the construction of roofs made of heavy and highly conductive material (e.g. concrete) as well as insulation material. During the day, the external insulation on the roof minimizes the heat gain from solar radiation. The cooled roof mass can then act as a heat sink, and absorb, through the ceiling, the heat penetrating into and generated inside the building during the daytime hours. This system is effective and related to radiant heat loss during the night [48].

6.1.4. Evaporative cooling

Evaporative cooling takes advantage of fresh air currents to cool buildings by means of the direct or indirect evaporation of the water in the air. One example of direct evaporation is the placement of wetted pads made of fibers in the windows. A drawback of this system, however, is that the pads block the view through the windows [48]. In indirect evaporation systems, the moisture content of indoor air does not increase. The air from the outside enters the roof, which is at a lower temperature. From there, the cool air is distributed throughout the building by means of convection. Examples of indirect evaporation are: (i) thatched rooftops that absorb moisture during the night, which then evaporates during the day; (ii) a pond on the roof [47]. This method conceived by Raman [49] (see Fig. 11) is one of the most effective and achieves the greatest reduction in indoor temperatures [47].

This system involves the installation of sack-cloth gunny bags or other dampened material to cool the air that enters the roof through the upper ventilation cavities. This is combined with a solar chimney to maintain the convective movement in the building, such that when the cool air comes into contact with this partition, it warms

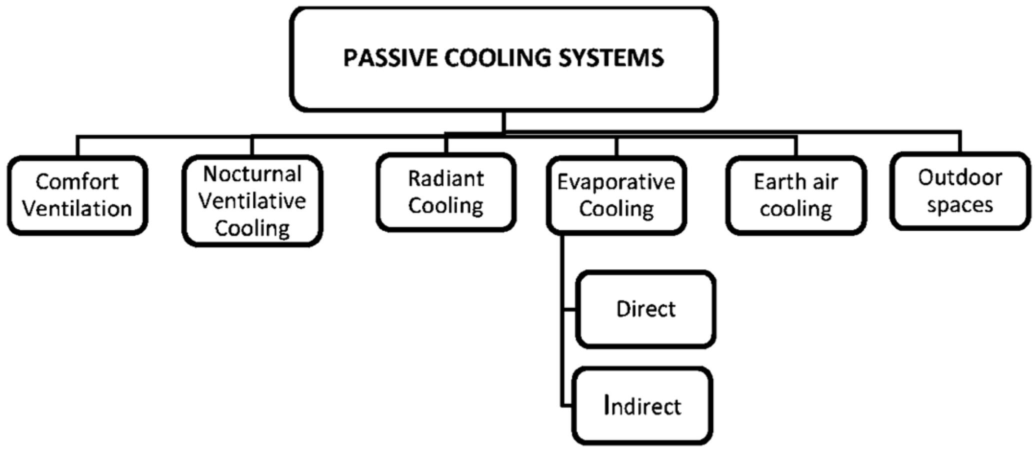

Fig. 9. Classification of passive cooling systems [50].

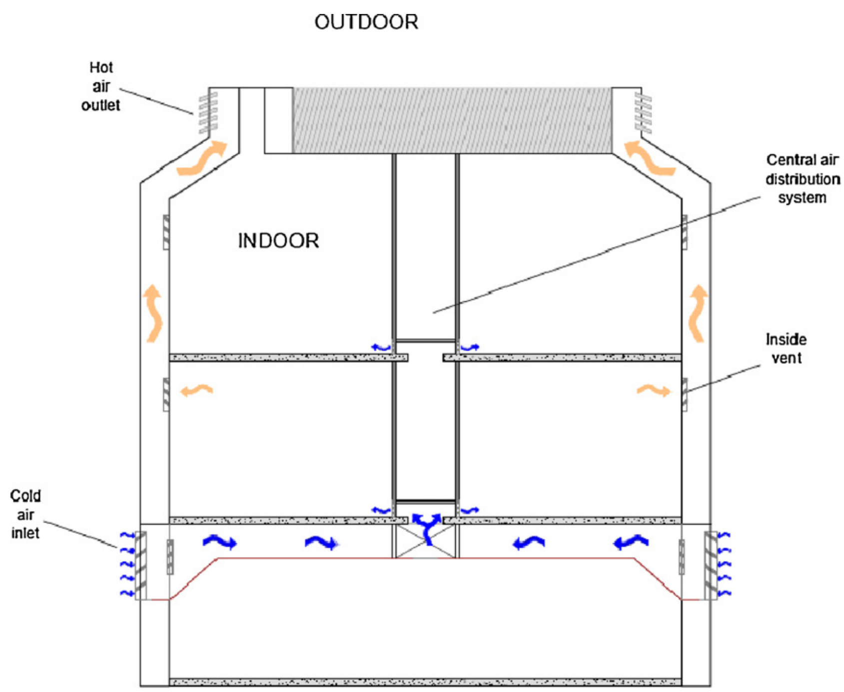

Fig. 10. Operation of a natural ventilation system.

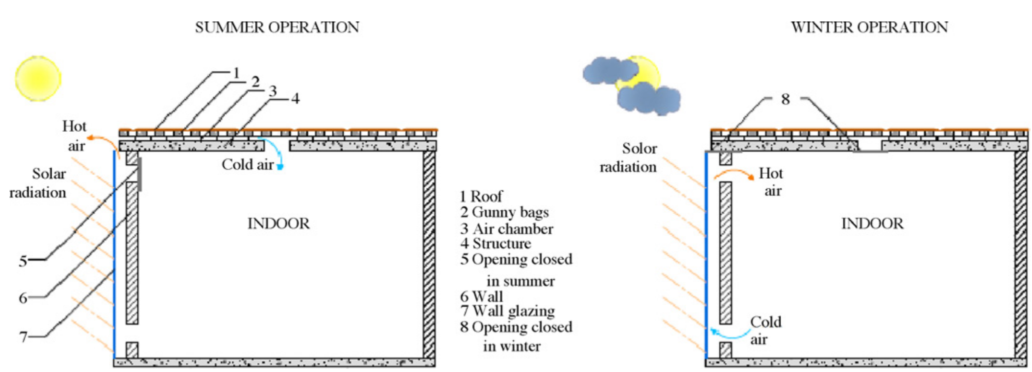

Fig. 11. Evaporative cooling system [49].

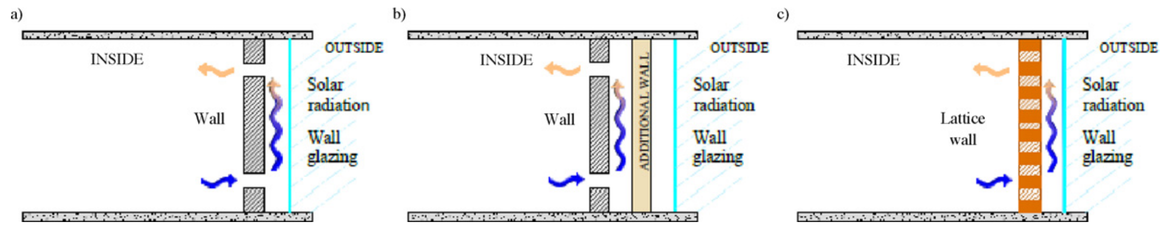

Fig. 12. Trombe wall models.

up, becomes less dense, goes up the wall, and leaves through its upper cavities. In winter, it can be beneficial to remove the wet bags, and thus modify the place where the air enters. This system maintains indoor temperatures 10 °C lower in summer and 15 °C higher in winter in relation to the outside temperature [49].

6.1.5. Earth-air cooling

Earth-air cooling takes advantage of the thermal inertia of earth to cool the building. In this type of system, buildings can be either totally or partially underground. Alternatively, underground air conducts can also be installed. In temperate climates, the natural temperature of the earth in summer at a depth of 2–3 m can be sufficiently low so that the earth can be used as a cooling source. In warmer climates, the natural temperature of the earth in summer is generally too high for this [48].

6.2. Passive heating

Passive heating options, based on thermo-physical properties as well as on the configuration of building envelopes can eliminate up to 2/3 of thermal discomfort [52]. The passive use of solar energy uses certain building elements (walls, roof, glazing) to store heat. The degree of effectiveness of these systems depends on climate conditions, construction materials, and the direct or indirect use of solar energy [8].

Enclosed spaces with direct solar gains, such as solariums, provide extra surface for the absorption of solar radiation as well as additional mass for its storage. They are the most effective systems for heating and daytime lighting in the building [52]. More research has been done on passive heating methods than on passive cooling methods [49]. Generally speaking, passive mechanisms work better when they operate in combination with each other [53]. The following sections describe the most important passive heating methods for buildings.

6.2.1. Trombe wall

A Trombe wall is a wall separated from the outdoors by glazing and an air cavity. It also has vents at the top and bottom of the interior wall, to control air flow. Solar energy is stored in the wall, and subsequently conveyed to the inside of the building by conduction. Hot air is released through upper air vents. Cold air enters the space between the wall and the glazing through the lower air vents, and comes in contact with the wall, which makes its temperature rise. Afterwards, the cycle begins again [53]. Many researchers have tried to improve the basic design. Fig. 12 shows various examples [53,54]: (a) a conventional Trombe wall design; (b) a Trombe-Michel wall with an insulation wall between the glazing and the wall; (c) a design in which the massive wall is replaced by a lattice wall).

The lattice wall improves thermal efficiency by almost 18% (obtaining an efficiency of up to 30.2%). It also has the advantage of using 35% less concrete in its construction [54].

6.2.2. Solar chimney

The solar chimney is based on natural convective air movement stemming from the variation in density of indoor air currents. In those cases in which the chimney is attached to the building wall, it operates similarly to the Trombe wall, and also provides benefits in the summer. Despite its positive results, the use of a solar chimney is not always feasible for aesthetic reasons [53]. Depending on the distribution and opening of air vents, the solar chimney can act as a natural ventilation system, passive heating method, or thermal insulation device, as shown in Fig. 13.

6.2.3. Unglazed transpired solar façade

This solar façade is composed of metal sheet with holes, as shown in Fig. 14. The outside metal cladding receives solar radiation, and the air that enters (with the help of a fan) through the holes to the inside of the building is thus heated. The heated air is then ducted into the building via a connection to the heating system. Experimental results show that this system can provide savings in energy consumption of up to 1 MWh/m^2 year, with an effectiveness of up to 63–68% [53]. It is also more economical to build than the Trombe wall.

7. Glazing

Window glazing is one of the weakest thermal control points in building interiors. In a standard family residence, 10–20% of all heat loss occurs through the windows [55].

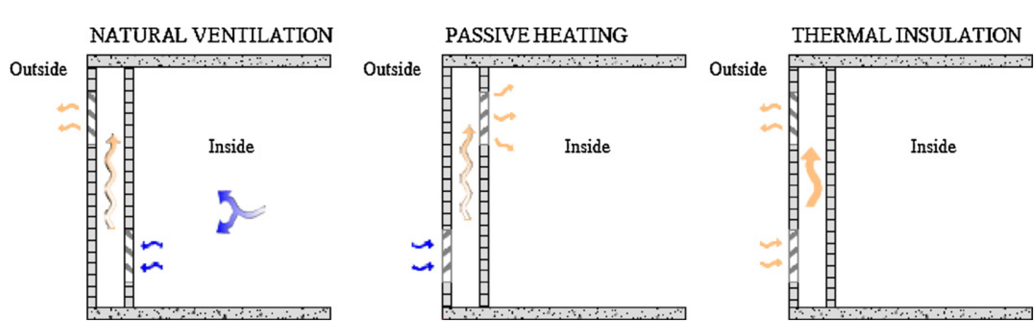

Fig. 13. Solar chimney models.

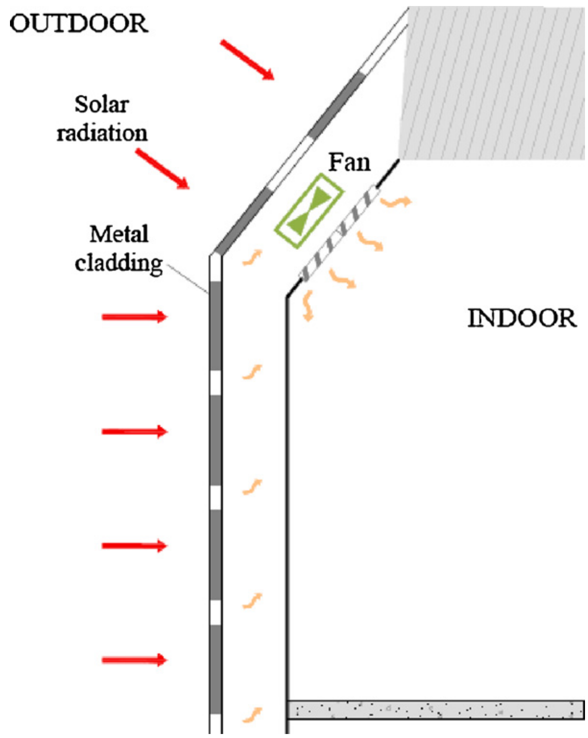

Fig. 14. Operation of solar façade.

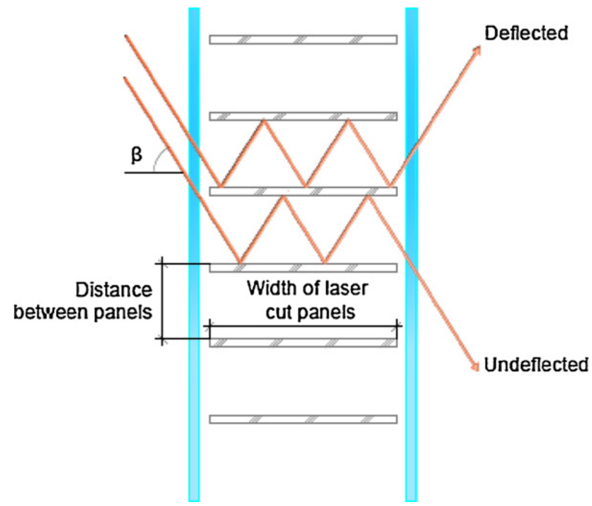

Fig. 15. Light transmission through angle-selective glazing.

7.1. *Thermal comfort and indoor illumination*

In glazing design, it is necessary to consider performance in terms of heat transfer, thermal comfort, light transmission, and appearance [56]. Window glazing that reduces the entry of solar radiation is most effective in summer and reduces the cooling demand. In contrast, in winter, this type of glazing increases the need for heating because it hinders the use of solar energy for passive heating. The development of glazing that reduces the quantity of solar radiation should not affect the possibility of seeing through windows, especially when a large amount of natural light is required, such as in office buildings. A reduction in natural daylight causes a corresponding increase in artificial light. This signifies higher energy costs and as well as an increase in indoor temperature [57]. Furthermore, design solutions that improve the amount of daylight entering windows are often associated with a potential risk of inside overheating [39,57] and an increase in the cooling demand in hot seasons when temperatures are high.

7.2. *Glazing types*

Glazing that provides energy savings can be classified in the following types [38]:

- Heat-absorbing glass: this glazing transforms solar radiation in heat energy (i.e. increasing its temperature), and distributing heat throughout the room by means of convection and radiation to reduce the direct radiation through the glass.
- Heat-reflecting glass: this glazing has a coating or film that blocks the entry of solar radiation into the building.
- Low radiation glass: this glazing also has a coating or film which reduces the heat transfer coefficient. It can also facilitate energy saving in winter.

7.3. *Film-plating glazing*

Film-plating glazing is treated with layers of another material to improve its thermal performance. The most common coating is done with metals (Cr, Ti, Ag and stainless steel), metal nitrides (CrN, TiN, ZrN), or metal oxides (SnO_2, TiO_2, ZnO). The coating layers can be low-emissivity films, reflective films, tinted films or spectrally selective coating. Generally, most of them involve a high-cost process [58].

The thermal performance of this glazing depends on its spectral properties. To evaluate its effectiveness in terms of thermal comfort and heat transmission, the total transmission properties and total absorption of the glass should be evaluated simultaneously [56].

The coating or film applied to the glazing reduces its transfer level and at the same time increases its absorption level. A high heat transfer intensifies the risk of overheating within the building. Moreover, a high absorption increases the temperature on the glazing surface. When the coating is applied to the glazing, this reduces the negative effect of the solar radiation on the building. However, the temperature of the glass surface reaches undesired levels and the level of natural illumination inside the building is reduced. Glazing with an additional coating (except for heat reflecting glass), which has a high heat transfer value, causes greater discomfort to the occupants [56].

Gijón-Rivera et al. [58] found a solution for this problem. They developed glazing with an internal coating that blocked the excessive heating of the glass. They evaluated the effectiveness of glazing coated with a combination of chemicals (SnS and Cu_xS) which limited the access of light and heat to the building. They found that the energy saving from the use of optimal glazing was influenced by the climate where the building is located.

7.4. *Angle-selective glazing*

The intensity of solar radiation depends on its angle of incidence. Solar rays with a larger angle (at noon and in the summer) provide more radiation. A system that selects the angle of the rays that enter the building can effectively control heat.

For this purpose, angle-selective devices can be embedded in the glazing, incorporated in new objects placed between the panes, or be part of elements attached to the inside or outside window frames. There are a wide variety of elements of this type, such as roller blinds, screens, fixed or mobile louvers, and even glass-enclosed surfaces for the redirection of sunlight entering the building [59].

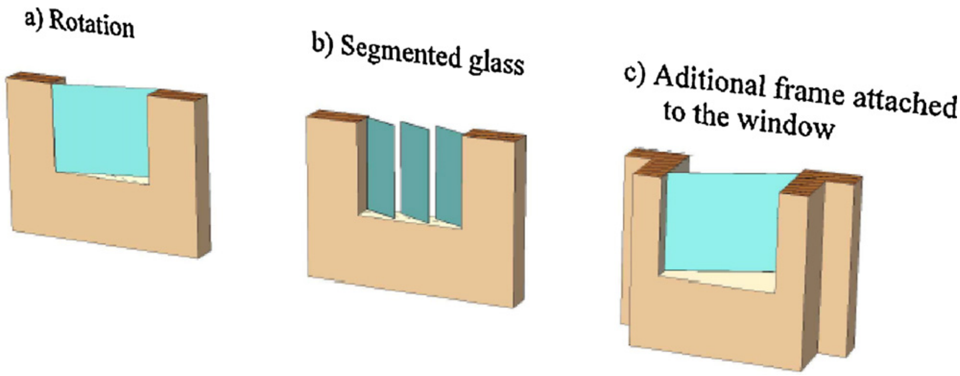

Fig. 16. Architectural solutions for glass rotation [60].

Reppel and Edmonds [57] developed glazing that was able to select the rays entering the building, depending on their incidence angle. This did not negatively affect the transparency of the glass. In this system, horizontal laser-cut panels were placed inside the glazing. When the sun rays came in contact with these panels, they underwent a series of reflections, which deflected them from their initial path. Based on the distance between the laser-cut panels as well as their width, these authors calculated the path of each sunray. They managed to deflect or reflect those rays with the largest incidence angle so that only those rays with a smaller angle could penetrate the building. They formulated the fraction of sunrays reflected as an equation based on the incidence angle. Fig. 15 shows how solar rays are transmitted through angle-selective glazing.

7.5. Glazing that provides spectrum selection

Still another option is to install glazing with spectrum selection, and thus control radiation according to wavelength [55,59].

7.6. Construction solutions

7.6.1. Glass rotation in respect to the building

Glass rotation effectively modifies the amount of heat entering the building through the windows. The modification of the angle between the glazing and the building façade involves changes in the intensity of the solar radiation received and thus in heat gains [60]. Construction solutions that amplify the rotation angle of the windowpane can considerably increase the area that receives sunlight, and thus, the solar heat gain. Saleh et al. used a computer simulation model to study the advantages of glass rotation. They found that, thanks to horizontal glass rotation, solar heat gains increased by a total of 63% in comparison to a simulation in which there was no glass rotation [60]. The main drawback of this system was that heat gains also increased in summer since this system is permanent and cannot be moved. The cooling was thus increased. Fig. 16 shows various solutions of this type.

7.6.2. Double glazing

Another way of optimizing window performance is through the use of double glazing. This is an effective method for both hot and cold climate conditions [58]. In hot climates, the best option is double clear glazing, and in cold climates, double glazing with a film coating that limits the heating of the window surface.

7.6.3. Advanced daylighting systems

The objective of advanced daylighting systems is for daylight to reach the center of the building spaces. The components of these systems are sunlight duct systems or solar tubes, solar panels located on the roof, optical collection systems, and special collection systems on the walls [59]. However, the performance of these systems is difficult to evaluate because of the complex nature of the angle-selection mechanisms.

8. Conclusions

1. The importance of energy consumption in the residential building sector makes it necessary not only to carry out basic research on the thermodynamic operation of the various systems designed to save energy. However, it is also necessary to formulate project criteria linked to the sustainability of these buildings. Based on the overview of recent research provided in this article, the following conclusions can be derived.
2. The sustainable design of buildings reduces the energy demand for heating and cooling.
3. The implementation of these measures in the project design phase reduces the final cost of the building.
4. The benefits of an energy-efficient building design should be evaluated for the entire life cycle of the building.
5. Factors with the greatest repercussion on the final energy demand are building orientation, shape, and the ratio between the external building surface and building volume.
6. Building design measures that are beneficial for one season of the year are not necessarily beneficial for the other seasons. Insulation systems should be developed that are capable of changing their configuration or performance as outside climate conditions vary.
7. A more energy-efficient building design does not necessarily coincide with more economical or more environmentally friendly designs.
8. Mobile shading devices offer greater benefits than fixed shading devices.
9. Conventional methods of estimating solar radiation lose their effectiveness as the urban area increases in density. More research is thus needed to determine the level of sunlight or diffuse radiation received in such areas.
10. More research should also be carried out on the influence of urban texture on the energy efficiency of city buildings.
11. The use of glazing that limits the access of radiation to a building should not affect the quality of inside illumination or brightness.
12. The study of optimal orientation and tilt improve the performance of solar panels. The angle of inclination depends on the operation of the installation. In this regard, panels should be tilted 10–25° if they only operate during months with high temperatures; 50–65% if they operate during months with low temperatures; and 30° if they operate all year around.

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